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Laser Cleaning for Pollution Prevention

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Abstract

The use of lasers to perform surface cleaning tasks is currently being investigated as a new alternative to traditional solvent and aqueous cleaning approaches for removal of contamination. Laser cleaning removes contaminants rapidly and directly with no cleaning

Aða agent@ð or secondary waste stream, thus minimizing waste disposal costs. It is particularly appropriate for precision cleaning operations where laser removal of contaminants to <2 mðg/cm2 has been demonstrated with short pulse Nd:YAG lasers. A review of current cleaning operations that may be suitable for laser cleaning technologies is presented. These operations include removal of oils and greases, adhesives, conformal coatings, and paint. A primary target application of the technology is preparation of surfaces for coating or bonding, but several niche applications such as preparation of circuit boards for repair may benefit. Physical mechanisms associated with different modes of contaminant removal are discussed and recent laser cleaning data acquired for some of these modes are presented. The results suggest that very compact, portable laser cleaning systems can be built employing hand-held laser cleaning end-effectors for fiber-optic delivered beams. Prototype laser cleaning system hardware is described briefly and scalability of laser technologies to meet several cleaning requirements will be summarized.

Introduction

Traditional methods of removal of organic contaminants and particles from metal surfaces in precision cleaning operations have employed cleaning agents such as chlorofluorocarbons (CFC=ðs) and other solvents that are now recognized as harmful to the environment or workers. Exposure of contaminated surfaces to laser beams with a sweep gas to carry away the effluent material ejected from the surface offers the potential for precision cleaning without any cleaning agent or secondary waste stream. For more than twenty years, researchers have been investigating the use of lasers to clean many contaminant or coating types from a variety of surfaces in applications ranging from art restoration,[1] surface decontamination,[2] and paint stripping,[3,4] to surface bond preparation,[5] wire insulation stripping,[6] and optics cleaning.[7] In recent years, extensive efforts have been devoted to research on laser removal of particulates from surfaces in the semiconductor and magnetic media manufacturing industries.[8-10] Only very recently has much research been devoted to the removal of oils and greases from metal surfaces.[11-14] This work demonstrated for the first time that precision cleaning goals (organic residue < 2 mðg/cm2) could be achieved in an open work environment without solvents or cleaning agents.

Cleaning surfaces with laser beams offers several advantages over use of conventional solvent and aqueous methods. Laser beam pulses are delivered to the surface in a simple one-step operation in which the contaminant is ejected into an effluent removal sweep gas. There are no cleaning agents to purchase, handle, store, recover, nor recycle and no heating, spraying, nor washing chambers/baths. The contaminant comes out in a minimally compact form for disposal (no secondary waste stream to process). The laser cleaning process is relatively fast, with area coverage rate limited only by average laser power available. There are no soak times nor drying times to be considered. The laser cleaning beam can be delivered remotely by fiber optics to provide the flexibility required for hand-held spot cleaning applications (e.g., flight line maintenance of aircraft). The nature of laser cleaning is such that precise areas can be processed without affecting adjacent areas, with the location precision limited only by the motion control methods employed. Laser cleaning is particularly appropriate for removing adherent coatings that otherwise require long soak times in harsh solvents, e.g. cured epoxy. On the other hand, laser cleaning is a line-of-sight technique and cannot easily get to soils in crevices or small enclosed volumes such as might occur in degreasing large numbers of intricate parts. The following sections provide preliminary information on those applications which may benefit from laser cleaning and on hardware approaches to implementing laser cleaning.

Potential Laser Cleaning Application Areas

A survey of aerospace cleaning requirements was undertaken to find areas where laser cleaning technology might contribute to pollution prevention in aircraft maintenance depot operations. These applications are discussed below along with the mechanism of contaminant removal by pulsed laser beams.

Removal of Oils and Greases

In many maintenance operations, solvent wiping has been used to clean oils, greases, and smut from surfaces. While widely used, the technique is polluting and does not always produce a known surface cleanliness level. Laser cleaning may be a useful replacement for solvent wiping in certain applications requiring cleaning to a low level of organic residue on the surface. An example of this type of operation is preparation of an aluminum-aircraft-skin crack area for composite patch repair. In the present approach, after the surface has been abraded to enhance adhesion of the bond layers, a solvent such as 2-butanol (MEK) is used to clean particles and organic residues from the surface. Scanning the area with a pulsed laser beam of appropriate intensity instead of solvent wiping will remove the abrasive grit, oil contaminants, and loosely attached aluminum particles created by the abrasion process. The result is a precision cleaned aluminum surface that should have good adhesive properties. No damage to the aluminum substrate occurs, because the laser pulses are sufficiently short that the heat absorbed has little time to conduct very far into the metal (about 1 mðm for a 16-ns pulse).

The mechanism of removal of oil and grease contaminants from metal surfaces by short laser pulses is still under investigation, but is thought to be a thermo-mechanical effect wherein the laser beam passes through the contaminant film (for visible and near infrared laser beam wavelengths), is partially absorbed by the metal, and ejects the contaminant as an aerosol by vaporization or shock expansion of a small amount of material at the contaminant/metal interface.14

Another example where laser cleaning may be useful is preparation of small areas of aircraft skin for touch-up painting. In this case, the area to be cleaned may have primed or painted regions in addition to metal area covered with contaminants such as hydraulic fluid. The metal areas are cleaned by the mechanism discussed above. The primed or painted areas can also be cleaned by a similar mechanism, however, the paint typically absorbs a higher fraction of the incident laser beam pulse and, therefore, lower beam energy per unit area (fluence) is required to achieve the same contaminant ejection effect.

Removal of Adhesives, Sealants, and Transparent Coatings

In earlier work,11 it was discovered that cured epoxy resin patches bonded to stainless steel could be easily removed with laser pulses in a simple Aðdebonding@ð process. In this case, the laser beam passes through the semi-transparent epoxy layer and is absorbed in the substrate metal. In one pulse the bond interface is opened as evidenced by light scattered from the gap created. The mechanism of breaking the bond is believed to be either a shearing stress from differential thermal expansion or shocks from vaporization of small quantities of interface material. After an area is scanned with overlapping pulses to create a continuous gap at the interface, the epoxy lifts off the surface in one piece for simple disposal.

In surveying potential applications of laser cleaning, it was found that there are other instances where it is of interest to remove transparent or semi-transparent coatings from surfaces. In repair of printed wiring assemblies, it is necessary to remove conformal coatings prior to removal and replacement of an individual component identified as defective. Conventional approaches entail either a solvent soak which removes the entire coating or local abrasion of the coating by various methods which may damage the assembly. By using the laser debonding mechanism, the coating can be removed over the solder pads or components of interest in a relatively quick clean operation. Another possible application is removal of sealant material from metal surfaces. In this case, the coating may have pigmentation which will inhibit the penetration of laser light to the substrate surface and the debonding mechanism will be complicated by absorption in the sealant.

Removal of Paint Coatings

There is a widespread need for environmentally friendly means of removing paint coatings. Lasers have been under investigation for several years3,4 for this application and paint removal systems have generally employed CO_2 lasers sized for large area decoating of surfaces. This wavelength of laser (10.6 mðm) is not well-suited for fiber optic delivery and remote or hand-held beam delivery is complex. The survey of applications suggested that there are some small-area paint removal requirements (such as detailing around masked areas) that would benefit from a compact hand-held beam delivery system such as those possible with the Nd:YAG laser (1.06 mðm). While very little paint removal research has been performed with YAG lasers, effective removal may be anticipated by ablation and thermal shock mechanisms. Paints typically contain heavy loadings of pigments which cause the laser beam to be absorbed over very short distances compared to the coating thickness. The paint heats and ablates layer by layer as pulses are applied to the surface. For short pulses that are possible with Nd:YAG lasers (10 ns), thermo-mechanical effects may enhance paint removal rates.

The applications outlined above are representative of a wide variety of needs for solvent-free cleaning approaches. Preliminary testing of the laser cleaning process on materials specific to these applications has just begun and selected test results are presented below.

Preliminary Test Results

A summary of the results of preliminary testing of laser cleaning techniques is given in Table 1. These tests were conducted on a few samples representative of the potential applications identified in the survey. Test coupons (1-inch by 2.25-inch) were exposed to a uniform fluence flat-top laser beam from a fiber-optic end-effector receiving pulses from a Nd:YAG laser (16-25 ns pulse width, 1.06 mðm wavelength, 20 Hz repetition rate). The coupons were scanned under the stationary beam with a computer-controlled motorized stage. Additional testing will be required to qualify the laser cleaning process for a given application that looks promising. The laser cleaning of sanded and grit-blasted aluminum for bond preparation was successful to the level of measurement available. More than three times the amount of grit and loose aluminum was removed with the laser than with a simple dry wipe at a pulse fluence of 1150 mJ/cm2. When the sample was contaminated with hydraulic fluid, this, too, was removed in the laser process. While bonding trials will be required to validate the laser approach, it is anticipated that the precision cleaning level achieved in laser cleaning of metals[14] will be sufficient for good bonding. When painted metal was contaminated with hydraulic fluid at a gross contamination level (2000

mðg/cm2), the fluid was removed in four passes at a relatively low pulse fluence of 290 mJ/cm2. Higher fluences should remove the fluid from the sample in one pass.

The removal of silicone and polyurethane conformal coatings from a solder surface was straightforward as expected, based on the previous data for removal of epoxy from metal. The coatings debonded from the metal surface in one pulse and scanning generated a continuous debonding gap in the area scanned. The coating was broken away from the edges of the area debonded by the laser by brushing with a plastic bristle brush. These coatings are fairly difficult to remove by alternative cleaning methods.

The removal of a 3.7 mil thick layer of MIL Spec paint (MIL-P-85582/MIL-C-85285) was accomplished effectively using the scanned pulsed laser beam. While paint removal was measured for a wide range of fluences, the most efficient removal was achieved for pulse fluences above 2000 mJ/cm2, where the effective heat of removal was about 3 kJ/g. The reduced fluence for removal was about 10 J/cm2/mil which is much less than that observed for pulsed CO_2 laser beams. The effluent plume contained a considerable amount of paint particles which confirms that thermal shocking is occurring in addition to simple ablation. This result has also been observed by Liu and Garmire[15] who used Nd:YAG pulses to remove thin acrylic paint coatings from surfaces.

Laser Cleaning Equipment

Implementation of laser cleaning in routine maintenance operations will require the development of custom compact hardware that is easy to use and accomplishes the target cleaning task reliably. The most likely form of a laser cleaning system for small-area cleaning tasks as outlined above will be a stand-alone cabinet with an umbilical connection to a remotely operated hand-held cleaning head. In form and operation, it will be similar to a vacuum cleaner with a hose connected cleaning tool. The cabinet will house a laser beam generator, beam conditioning optics, effluent control system, interface electronics, and a system controller. The umbilical cable will contain the beam delivery fiber optics, hoses for inlet and outlet effluent control gas flow, and electrical control wiring. The hand-held end-effector will contain optics for delivery of the beam to a surface, gas flow nozzles, sensors, and operator controls and indicators. This generic approach can be scaled within reason over a range of applications with different laser power requirements. For example, the smallest system might be for conformal coating removal where only an occasional pulse or two might be required to debond coating over a solder pad or component (1 W laser power). In this case, an external vacuum system might remove the effluent. At the other end of the small-area processing spectrum, might be the paint removal application, where removal rates are more critical. The laser cleaning technique is linearly scalable in the sense that area coverage rates are proportional to average laser power. As an example, consider the power required to remove 1 ft2 (929 cm2) of paint (0.0037-inch thick) in a critical area not processed by alternative methods. Using a value of 10 J/cm2/mil, the total beam energy required is 34.4 kJ. If 12 minutes can be allotted to the task, the average laser power required is 48 watts. Higher laser powers would permit faster removal rates. It should be noted that the entire paint removal task is completed in the 12 minutes since there is no surface preparation nor residue cleanup.

Table 1. Summary of preliminary test results.

Sample Type Fluence per Pulse (mJ/cm2) Comment
7075 T-6 Clad Al abraded with 320 grit aluminum oxide paper or 27
mðm grit blast; dry
wiped
1150
Surface cleaned of grit and loosely held aluminum in one
pass*

7075 T-6 Clad Al abraded with 320 grit aluminum oxide
paper or 27 mðm grit blast; contaminated with 20-25
mðg/cm2 hydraulic fluid
1150
Surface cleaned of grit, loosely held aluminum, and
hydraulic fluid in one pass

Grey painted 2024 T-3 Al (MIL-P-85582/MIL-C-85285), 3.7
mils thick; contaminated with 2000 mðg/cm2 hydraulic
fluid
290

Surface cleaned of hydraulic fluid in four passes
MS-460A Silicone Conformal Coating on solder (3 coats)
750
Debonded coating in one pass; removed from edge attachment with brush
MS-470N Urethane Conformal Coating on solder (3 coats)
750
Debonded coating in one pass; removed from edge attachment with brush
Grey painted 2024 T-3 Al (MIL-P-85582/MIL-C-85285), 3.7 mils thick
2360
Paint coating removed in two passes * 7.6 pulses per pass

Conclusions

The preliminary results of laser cleaning research on practical aerospace cleaning problems suggest that there are several areas where pulsed laser technology may make a contribution to pollution prevention through reduced use of solvents. Areas showing promise for the introduction of laser cleaning technology include preparation of surfaces for adhesive bonding and for touch-up painting, removal of conformal coatings, and removal of paint in critical small-area detailing.

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